Cosmological Insights from SZE and X-ray Selected Cluster Samples

Joe Mohr with
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for DES, SPT and eROSITA

Panchromatic Panoramic Studies of Galaxy Clusters
ASIAA, Taipei, 12. March 2019

LMU- Munich
MPE- Garching
Overview

- Preliminaries:
  - Motivation, cluster selection and sample contamination

- SPT cosmology and mass calibration
- X-ray cluster finding over the DES area
- Prospects for eROSITA cluster cosmology

The primary references discussed in the talk:

Bocquet+18: *SPT Cluster Cosmology Constraints with Weak Lensing*

Klein+18a: *New method of confirming X-ray and SZE selected clusters (MCMF)*
[http://adsabs.harvard.edu/abs/2018MNRAS.474.3324K](http://adsabs.harvard.edu/abs/2018MNRAS.474.3324K)

Klein+18b: *New Catalog of 2000 RASS Clusters over DES Area*

Grandis+18: *Forecasts of cluster cosmology for eROSITA*
Motivation

- X-ray & SZE cluster surveys → Cosmology!

- Also: baryon content, mass accretion history, AGN/star formation feedback, etc

- New deep/wide optical survey data (e.g., 5000 deg$^2$ DES or HSC, KiDS) available w/ Euclid+LSST coming

- Goal: understand how best to combine DES with SZE/X-ray surveys for improved cluster selection and weak lensing mass calibration
Cluster Selection Methods

- Cluster finding: SZE, X-ray and Optical

In all cases, use cluster Red Sequence galaxies to estimate redshift
Cluster Selection Methods

- Cluster finding: SZE, X-ray and Optical
  - Use cluster Red Sequence galaxies to estimate redshift

- Selection in observable implies mass selection, given a mass-observable relation
  - Typically power law
  - Scatter in obs at fixed mass combines intrinsic & measurement components
  - Cosmology dependence easily modeled
  - Calibration through weak lensing, dynamical constraints
In SZE samples, contamination only through noise fluctuations
- To reasonable approx, only the cluster virial regions produce signal
- SPT cosmology sample starts with ~5% cont.
- Optical confirmation pushes to <1% cont.

In X-ray samples, contamination through AGN and noise fluctuations
- To good approx, only virial regions produce signal
- With good angular resolution one excludes unresolved AGN (~10% cont.)
- Optical confirmation pushes contamination to <1% cont.

In X-ray/SZE cluster cosmology, the primary challenge is mass calibration (: use weak lensing).

In Red Sequence samples, contamination through projection effects
- RS galaxies present in all cosmic structures
- Must model the contamination in cosmological analysis

In optical cluster cosmology, the challenges are mass calibration and also modeling contamination.
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SPT-SZ Sample
Song+12 (720 deg$^2$), Bleem+15 (2500 deg$^2$)

- 2500 deg$^2$ sample
  - 516 at $\xi > 4.5$
  - 387 at $\xi > 5.0$
  - Bleem+15

- High z subsample
  - 36 at $z > 1$
  - Max $z_{\text{spec}} = 1.47$
  - Bayliss+13
  - Max $z_{\text{phot}} = 1.72$
  - Strazzullo+18

- Clean sample with $M_{500} > 3 \times 10^{14} M_\odot$ to $z \sim 1.7$
**Bayesian Framework:**

- Forward model from halo mass function to observable-redshift distribution
- Adopt astrophysical observable-mass scaling relation (4+ params)
- Calibrate empirically using weak lensing

Then: explore parameter space using MCMC
Cosmology analysis coupled to empirical mass calibration with WL

Success implies: validated cluster sample

e.g., well understood selection, no/low contamination, masses calibrated accurately

Then: SPT single cluster masses ~25% uncertain (15% of this systematic)
: cluster physics studies can proceed!
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The Data: DES and RASS

- 5000 deg$^2$ griz imaging over ~600 nights on Blanco 4m
- Survey stats: ~0.9” FWHM riz ~2 mags deeper than SDSS
  - Adopting Year 3 catalogs and images

- ROSAT All Sky (X-ray) Survey, 2x10$^4$ sources over DES (<10% clusters)
- Survey stats: ~1.5’ FWHM (clusters unresolved at z>0.3)
  - Adopting RASS faint source reanalysis- 2RXS (Boller+16)

RASS Exposure over DES region
Tool for Identifying Clusters in RASS: Multi-Component Matched Filter (MCMF)  
Klein+18a

- Designed for cluster confirmation and redshift estimation using priors from X-ray or SZE survey
  - Aperture scales with mass
    - $R_{500}$ given mass proxy and redshift guess
  - Galaxies weighted by radial distance
  - Colors $g-r$, $r-i$, $i-z$ used simultaneously
  - Galaxies weighted by distance to RS
  - Studies of random positions allow one to quantify chance superpositions

- Empirical calibration of RS colors/widths using $\sim 10^3$ clusters that have spec-z's
MCMF Examples
Klein+18a

- Search w/candidate priors produces richness(z) or $\lambda(z)$
- Fit peaks (asymmetric) to measure photo-z (and uncertainty)
  - Spectacular performance of photo-z’s (RMS[$\Delta z/(1+z)$]~0.005)
Probability of source being random superposition (contamination) can be quantified using richness $\lambda$ distributions along random lines of sight
- $f_{\text{cont}} < 0.05 \rightarrow 5\%$ random superposition

In addition, RASS AGN often have IR sources (WISE). AGN are outliers in richness to luminosity distribution compared to clusters
- this cut reduces contamination by ~50%
- So $f_{\text{cont}} < 0.05 \rightarrow 2.5\%$ final contamination

This solves problems that have plagued e.g., CODEX and MACS samples.

$$f_{\text{cont},i} = \frac{\int_{\lambda_i}^{\infty} f_{\text{rand}}(\lambda) d\lambda}{\int_{\lambda_i}^{\infty} f_{\text{obs}}(\lambda) d\lambda},$$
z>0.5 Examples
Each MARD-Y3 cluster has flux, redshift, X-ray luminosity

Using calibrated $L_x$-mass relation (Bulbul+18), we also provide mass estimates for each cluster

Mass sensitivity of SPT-SZ and MARD-Y3 similar at $z \sim 0.5$

1086 RASS clusters over 5000 deg$^2$ with 2.6% contamination.

SPT-SZ $\sim 7x$ higher density than REFLEX

Extends to $z \sim 1$ (100+ at $z > 0.5$)
Points: MARD-Y3 $f_{\text{cont}} < 0.05$ sample LFs
- 1086 clusters, 2.6% cont
- corrected to flux limited sample (from S/N selected)

Lines: Forward modeled HMF using SPT cosmology (Bocquet+18) and $L_x$-mass relation (Bulbul+18)

Quantitative validation underway. Cosmology possible with DES WL mass calibration
SPT+DES Improvements through MCMF
Klein+ in prep

- SPT-SZ+DES analysis improves photo-z’s, pushes to lower S/N
  - 300 additional clusters identified between 4<S/N<4.5 → full SPT-SZ sample 816
- SPTpol+DES(+WISE) analysis provides sample of 321 clusters
  - 112 are overlapping, so total SPT sample is 1025 (~1300 including SPECS fields)

SPT-3G operating!
Direct Mass Calibration
Grandis+19 (archiv/1810.10553)

- Tremendous additional robustness comes with well calibrated shear and photo-z catalogs from DES (or HSC, KiDS)

- Weak lensing mass calibration
  - Adopt individual shear profiles and redshift distribution as constraints
  - At each iteration in chain (7 cosmo, 4 scaling, 2 nuisance) solve for masses

- Our approach empirically constrains mass-obs relation (including scatter!)

Figure 2 from eROSITA forecast paper
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Can we probe ICM in groups?

- **Launch**: From Baykonour, Proton–Block-DM  
  **June/July 2019**
- **3 Months**: flight to L2, PV and calibration phase
- **4 years**: 8 all sky surveys (**eRASS:1-8**; scanning mode: 6 rotations/day)  
  - Re-visit LMC & SMC every ~month  
    (to L_{0.5-2 \text{ keV}} \sim 10^{34} \text{ erg/s})
- **2.5 years**: pointed observations, including ~20% GTO. 1 AO per year
- **Ground Segment**: 2 x 70m antennae (Bear Lakes and Ussirisk), daily contact (up to ~4 hours); telemetry transfer directly to MPE via Moscow NPOL/IKI Control Center
The “robust cosmology sample”

- \( n_\gamma > 40 \)
- Existence at 6\( \sigma \)
- Extension at 3\( \sigma \) (Grandis+i.p.)
- Low contamination

\[ M_{\text{obs}} > 2 \times 10^{14} M_\odot \]

Cosmological modelling

affected by baryon feedback
e.g. mass function Bocquet+16

- Total: 11k
- 0.5, 1.0: 5.3k
- 1.0: 0.4k

\( M_{500c} \) vs. \( z \) plot with
- \( n_\gamma = 40 \)
- \( n_\gamma = 15 \)
- \( M = 2 \times 10^{14} M_\odot \)
- \( M = 5 \times 10^{13} M_\odot \)
The “maximal sample”

# clusters

$M_{500c} \, [M_\odot]$

$10^{15}$

$10^{14}$

$10^{13}$

$10^{12}$

$10^{11}$

$10^{10}$

$10^9$

$10^8$

$10^7$

$10^6$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

$z$

$n_\gamma > 15$

Existence at $3\sigma$

No extent information

Higher contamination, no extent information

Require cleaning with deep optical data ($z<1.1$) + IR data ($z>1.1$)

Klein+18, i.p.

<table>
<thead>
<tr>
<th>Total</th>
<th>$(0.5, 1.)$</th>
<th>$1. &lt;$</th>
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<tbody>
<tr>
<td>93k</td>
<td>28k</td>
<td>2.6k</td>
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Summary

X-ray/SZE+optical wide area surveys offer big advantages

● Larger numbers of clusters → implies more precise cosmology
● Lower sample contamination → implies more robust cosmology
● Weak lensing mass calibration → implies more accurate cosmology

Demonstration on X-ray(RASS) and SZE(SPT) surveys

● ~1000 new RASS selected clusters overlapping DES
● Doubling of SPT sample to ~1025

eROSITA sample 1 to 2 orders of magnitude larger still

● Promising sample for cosmology and structure formation studies
**Focus:**
- Observational cosmology and structure formation studies

**Survey Projects**
- South Pole Telescope
- Dark Energy Survey
- eROSITA
- Euclid and LSST
- D-MeerKAT

**Group Members:**

*Research Scientists*
- Sebastian Bocquet
- Matthias Klein
- Veronica Strazzullo

*Euclid subgroup*
- Martin Kümmel
- Holger Israel
- Thomas Vassallo
- Koshy George

*Postdoc Fellows*
- Natasha Maddox
- Maurillio Panella
  +Searching!

*PhD Students*
- Raffaella Capasso
- Sebastian Grandis
- Maria Paulus
- Peter Lustig
  +Searching!

**Some past members**
- Kai-Feng Chen, Dr. Nikhel Gupta (Melbourne), Dr. I-Non Chiu (ASIAA),
- Dr. David Rapetti (UC Boulder), Prof. Alex Saro (Trieste), Prof. Shantanu Desai (IIT, Hyderabad),
- Prof. Yen-Ting Lin (ASIAA), Prof. Subha Majumdar (TIFR)
References to Recent Papers from LMU Group

- Capasso+19  Dynamical Study of SPT clusters
  - http://adsabs.harvard.edu/abs/2019MNRAS.482.1043C

- Bulbul+18 X-ray scaling relations to z~1.3

- Chiu+18 Baryonic scaling relations to z~1.3
  - http://adsabs.harvard.edu/abs/2018MNRAS.478.3072C

- Grandis+18 Forecasts of cluster cosmology for eROSITA

- Klein+18 New method of confirming X-ray and SZE selected clusters
  - http://adsabs.harvard.edu/abs/2018MNRAS.474.3324K

- Stern+18  Weak lensing mass calibration using DES data

- Strazzullo+18 Study of galaxy population in 5 highest z SPT clusters with HST/Spitzer
  - http://adsabs.harvard.edu/abs/2018arXiv180709768S

- Dietrich+17 WL mass calibration using Magellan and HST imaging
  - http://adsabs.harvard.edu/abs/2017arXiv171105344D

- Gupta+17 Study of cluster radio galaxies
  - http://adsabs.harvard.edu/abs/2017MNRAS.467.3737G

- Hennig+17  Study of SPT cluster galaxy populations to z~1.1
  - http://adsabs.harvard.edu/abs/2017MNRAS.467.4015H

- Chiu+16 Stellar masses in low mass clusters and groups
  - http://adsabs.harvard.edu/abs/2016MNRAS.458..379C

- Chiu+16 Baryonic properties in z~0.9 SPT clusters
  - http://adsabs.harvard.edu/abs/2016MNRAS.455..258C